Physics Letters B 728 (2014) 165–169

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Heating of ions with a Kappa velocity distribution by a non-resonant Alfvén wave ☆

Hai-Feng Liu (刘海峰) [a,b,*], Shi-Qing Wang (王世庆) [a,b], Ke-Hua Li (李克华) [b,*], Ming Yin (殷明) [b], Wen-Zhong Li (郦文忠) [b], Jia-Qing Miao (苗加庆) [b], Jing-Jing Hou (候景景) [a]

[a] Southwestern Institute of Physics, Chengdu 610041, China
[b] The Engineering and Technical College of Chengdu University of Technology, Leshan 614000, China

ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 7 November 2013
Accepted 8 November 2013
Available online 22 November 2013
Editor: S. Dodelson

ABSTRACT

In this study, the heating of ions with a Kappa (κ) velocity distribution by an Alfvén wave propagating along an external magnetic field via non-resonant wave–particle interactions in low-beta plasmas is investigated by means of both quasilinear theory and test-particle simulation. The κ velocity distribution is most suitable for describing a non-thermal distribution with an enhanced high-energy tail and includes the Boltzmann distribution as a limiting case. Because of the thermal non-equilibrium factor (κ factor), the heating effect of κ ions is weaker than that of Boltzmann ions, and when $\kappa \to \infty$, the heating effects become identical. It is determined that the ion pickup increases as the κ parameter increases, and the heating is dominant in the perpendicular (to the background magnetic field) direction. Subsequently, during the heating process, ions are also accelerated in the parallel direction. This phenomenon may have relevance to the heating of ions in the solar corona and to ion heating in some toroidal-confinement fusion devices.

1. Introduction

The heating of ions by an Alfvén wave is a significant topic in astrophysical and magnetically controlled laboratory plasmas [1–6] and, therefore, has been studied extensively both experimentally and theoretically. According to linear Vlasov theory, cyclotron resonance between the ions and the Alfvén wave propagating along the external magnetic field occurs if $w - kv_{//} = n\Omega_i$, where ω, $v_{//}$, n, Ω_i and k denote the wave frequency, the wave number, the ion velocity component parallel to the magnetic field, an integer, and the ion cyclotron frequency, respectively. Snyder [7] has proposed that an Alfvén wave can heat the ions via nonlinear interactions. Hasegawa and Chen [8] have found that Alfvén-wave phase mixing, which is caused by non-uniformity in plasmas, can heat the plasma. If the wavelength is smaller than the cyclotron radius, the resonance condition is that the wave frequency should be an integral multiple of the ion cyclotron frequency [9]. Chen et al. [10,11] have investigated stochastic ion heating by obliquely propagating a large-amplitude Alfvén wave and have found that significant perpendicular heating of the ions can occur at a fractional frequency. Using a test-particle approach, Wu et al. [12] have found that initially unaffected ions can be picked up by a propagating Alfvén wave, and Li et al. [13] have numerically verified the ion pickup using a self-consistent model. Guo et al. [14] have demonstrated analytically and numerically that ions can be heated by a low-frequency linearly polarized obliquely propagating shear Alfvén wave. However, the linear resonance condition is valid only if the wave amplitude is vanishingly small. Recently, a new process has been proposed [15,16]. It has been suggested that protons can be heated by turbulent Alfvén waves via non-resonant interactions. Such a process is efficient in low-beta plasmas. The process can be demonstrated using two entirely different theoretical methods. The major finding is that turbulent Alfvén waves can lead to enhanced stochastic ion motion. The key to the heating process is pitch-angle scattering [15]. Miller has shown that in solar flares, an Alfvén wave can heat protons via nonlinear Landau damping [17]. Evidence of ion heating by low-frequency Alfvén waves has also been found in laboratory plasmas [18–21].

In existing studies of the heating of ions by an Alfvén wave, the most commonly used model is that of a thermal plasma. Measurements of plasmas and magnetic fields, however, obtained by spacecraft in planetary magnetospheres and the solar wind have provided important, if not unique, access to the study of cosmic plasmas. One major finding is that the observed velocity-space

* Corresponding author.
E-mail addresses: blessingfeng@gmail.com (H.-F. Liu), lkh07392006@163.com (K.-H. Li).

0370-2693/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physletb.2013.11.018

distributions have been shown to exhibit a non-Maxwellian form and can instead be modeled using the more general κ function, which can incorporate the suprathermal population [22–25]. There are already many studies of such velocity distributions in various areas of fundamental and space-plasma physics [26–28]. The advantage of employing the κ distribution lies in the fact that the Boltzmann distribution is a special case of the κ function in the limit of $\kappa \to \infty$. The modified solutions to earlier results that were derived on the basis of the Boltzmann velocity distribution thus represent more general cases. In addition to its mathematical generality, the κ velocity distribution, like the Boltzmann function, is also a special class of solutions to the Vlasov equation. An attempt has been made to derive the κ velocity distribution from first principles [29–33]. Treumann and Jaroschek [34] have shown that the κ distribution describes marginally stable Gibbs equilibria far from thermal equilibrium and should be valid for collisionless plasmas with fully developed quasi-stationary turbulence.

The objective of the present investigation is to study the heating of κ ions by an Alfvén wave. From the evolution of the velocity distribution and temperature of the ions, we obtain a scaling law for non-resonant ion heating and confirm the ion pickup caused by non-resonant interactions between the Alfvén wave and the ions.

2. Analytic theory

Let us begin with the κ distribution function for a free system, which can be written as follows [35]:

$$f_\kappa(v) = \frac{1}{(\sqrt{\pi}\theta)^3}\frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)}\left(1+\frac{v^2}{\kappa\theta^2}\right)^{-(\kappa+1)} \tag{1}$$

where κ is the spectral index, Γ is the gamma function, and the thermal speed θ is related to the particle kinetic (physical) temperature T_κ by

$$\theta = \left[(2\kappa-3)/2\kappa\right]^{1/2}(2k_B T_\kappa/m)^{1/2} \tag{2}$$

We consider the motion of charged particles in a thermal non-equilibrium plasma in the Alfvén waves for $\beta = (\theta/v_A)^2 = 0.01$. For simplicity, we assume that the Alfvén waves propagate along a constant background magnetic field $\boldsymbol{B}_0 = B_0\boldsymbol{i}_z$, and they satisfy the dispersion relation $\omega = kv_A$, where ω and k are the wave frequency and wave number, respectively, and $v_A = B_0/(4\pi n_0 m_i)^{1/2}$ is the phase speed of the Alfvén waves, where n_0 and m_i are the plasma density and ion mass, respectively [12,13]. The magnetic and electric fields of the Alfvén waves can be expressed as

$$\delta\boldsymbol{B}_w = \sum_{k=1}^{N}\boldsymbol{B}_k[\cos\phi_k\boldsymbol{i}_x \pm \sin\phi_k\boldsymbol{i}_y] \tag{3}$$

$$\delta\boldsymbol{E}_w = -v_A\boldsymbol{i}_z \times \delta\boldsymbol{B}_w \tag{4}$$

where the plus and minus signs in Eq. (3) correspond to right-hand (RH) and left-hand (LH) polarized Alfvén waves, respectively; $\boldsymbol{i}_x$ and $\boldsymbol{i}_y$ are unit vectors; $\phi_k = k(v_At - z) + \varphi_k$ is the wave phase; φ_k is the (random) phase of the mode k; and N is the total number of wave modes. The particle motion in the Alfvén wave fields is given by

$$\frac{d\boldsymbol{v}}{dt} = \frac{q_i}{m_i}\left[\boldsymbol{v}\times(\boldsymbol{B}_0+\delta\boldsymbol{B}_w)+\delta\boldsymbol{E}_w\right] \tag{5}$$

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v} \tag{6}$$

where the subscript i indicates physical quantities associated with the ion species i. Here, we are concerned with only one Alfvén wave ($N=1$). Without loss of generality, we can set $\varphi_1 = 0$. In the following analysis, we consider the interaction between the RH-polarized Alfvén wave and protons. Eq. (1) can be rewritten as

$$\delta B_W = B_k e^{-i\phi_k} \tag{7}$$

Let $u_\perp = v_x + iv_y$ and $v_{/\!/} = v_z$; then, we have

$$\frac{du_\perp}{dt} + i\Omega_p u_\perp = i(v_{/\!/} - v_A)\Omega_k e^{-i\phi_k} \tag{8}$$

$$\frac{dv_{/\!/}}{dt} = -\operatorname{Im}\left(u_\perp\Omega_k e^{i\phi_k}\right) \tag{9}$$

$$\frac{dz}{dt} = v_{/\!/} \tag{10}$$

where $\Omega_p = \frac{eB_0}{m_p}$ is the proton cyclotron frequency, and in the lowest order, $v_{/\!/} = v_{/\!/}(0)$, where $v_{/\!/}(0)$ is the initial proton parallel velocity, which is a constant. This approximation is valid when $\frac{\Omega_k}{\Omega_p} = \frac{B_k}{B_0} \ll 1$, such that $|\Omega_p| \gg |k[v_{/\!/}(0) - v_A]|$. For the initial conditions $u_\perp = u_\perp(0)$ and $z = z(0)$, the solution of Eq. (8) for a low-beta plasma is [12]

$$u_\perp = u_\perp(0)e^{-i\Omega_p t} - v_A\frac{B_k}{B_0}e^{-ik(v_At-z)} + v_A\frac{B_k}{B_0}e^{ikz(0)}e^{-i\Omega_p t} \tag{11}$$

where $\Omega_p - k[v_A - v_{/\!/}(0)] \approx \Omega_p$, $z = z(0) + v_{/\!/}(0)t$, and $v_A - v_{/\!/}(0) \approx v_A$. The first term in $u_\perp$ is the gyromotion of the proton in the background magnetic field, the second term is the modification of the gyromotion by the Alfvén wave, and the last term corresponds to the perturbed proton velocity in the Alfvén wave [37]. The average transverse velocity at position z can be written as

$$\begin{aligned} U_\perp = {} & -v_A\frac{B_k}{B_0}e^{-ik(v_At-z)} \\ & + \frac{1}{\sqrt{\pi}\theta}\frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)}\int_{-\infty}^{\infty} v_A\frac{B_k}{B_0}e^{ik[z-v_{/\!/}(0)t]}e^{-i\Omega_p t} \\ & \times\left(1+\frac{v_{/\!/}^2(0)}{\kappa\theta^2}\right)^{-(\kappa+1)} dv_{/\!/}(0) \end{aligned} \tag{12}$$

From Eq. (12), we are unable to obtain an exact solution, so we consider the assumption [35] $(1+\frac{v_{/\!/}^2}{\kappa\theta^2})^{-(\kappa+1)} \approx e^{\frac{v_{/\!/}^2}{\theta^2}} - \frac{v_{/\!/}^2}{\kappa\theta^2}$, where $|\frac{v_{/\!/}^2}{\kappa\theta^2}| \ll 1$. Eq. (12) can be rewritten as

$$\begin{aligned} U_\perp = {} & -v_A\frac{B_k}{B_0}e^{-ik(v_At-z)} + \frac{v_A A_k\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)}\frac{B_k}{B_0}e^{ikz}e^{-i\Omega_p t} \\ & - \frac{1}{\sqrt{\pi}\theta}\frac{2v_A\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)}\frac{B_k}{B_0}\frac{1}{(k\theta t)^2\kappa}e^{ikz}e^{-i\Omega_p t} \\ & \times\int_{-\infty}^{\infty}\cos\left(kv_{/\!/}(0)t\right)dv_{/\!/}(0) \end{aligned} \tag{13}$$

where $A_k = (1/\sqrt{\pi})\int_{-\infty}^{\infty}\cos(k\theta tx)e^{-x^2}dx = e^{-k^2\theta^2t^2/4}$. This average transverse velocity demonstrates the pickup of the proton by the Alfvén wave. The corresponding perpendicular proton temperature is

$$\begin{aligned} T_\perp = {} & \frac{m_p}{2k_B}\frac{1}{\sqrt{\pi}\theta}\frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)} \\ & \times\int_{-\infty}^{\infty}|u_\perp - U_\perp|^2\left(1+\frac{v_{/\!/}^2(0)}{\kappa\theta^2}\right)^{-(\kappa+1)} dv_{/\!/}(0) \end{aligned}$$

$$= T_\kappa \left(1 + \frac{2\kappa - 3}{2\kappa}\frac{1}{\theta^2}\frac{v_A^2 B_k^2}{B_0^2}\left\{1 - \left[\frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)}A_k\right]^2 + 12\left[\frac{1}{\sqrt{\pi}}\frac{\Gamma(\kappa+1)}{\theta\kappa^{3/2}\Gamma(\kappa-1/2)}\frac{1}{(k\theta t)^2\kappa} \times \int_{-\infty}^{\infty}\cos\big(kv_{//}(0)t\big)\,dv_{//}(0)\right]^2 + 4\frac{A_k}{\sqrt{\pi}}\left[\frac{\Gamma(\kappa+1)}{\theta\kappa^{3/2}\Gamma(\kappa-1/2)}\right]^2\frac{1}{(k\theta t)^2\kappa} \times \int_{-\infty}^{\infty}\cos\big(kv_{//}(0)t\big)\,dv_{//}(0)\right\}\right) \tag{14}$$

Using the same procedure, the average parallel velocity is then found to be

$$U_{//} = v_A\frac{B_k^2}{B_0^2}\left[1 - A_k\frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma(\kappa-1/2)}\cos(\Omega_p t - kv_A t) - \frac{1}{\sqrt{\pi}}\frac{\Gamma(\kappa+1)}{\theta\kappa^{3/2}\Gamma(\kappa-1/2)}\frac{1}{(k\theta t)^2\kappa}\cos(\Omega_p t - kv_A t) \times \int_{-\infty}^{\infty}\cos\big(kv_{//}(0)t\big)\,dv_{//}(0)\right] \tag{15}$$

for $t \to \infty$, $A_k \to 0$ and

$$\frac{\int_{-\infty}^{\infty}\cos(kv_{//}(0)t)\,dv_{//}(0)}{(k\theta t)^2} \to 0.$$

Therefore, the asymptotic values of the average parallel and transverse velocities and the perpendicular temperature are

$$U_{//} = v_A\frac{B_k^2}{B_0^2} \tag{16}$$

$$U_\perp = -v_A\frac{B_k}{B_0}e^{-ik(v_A t - z)} \tag{17}$$

$$T_\perp = T_\kappa\left(1 + \frac{2\kappa-3}{2\kappa}\frac{v_A^2}{\theta^2}\frac{B_k^2}{B_0^2}\right) \tag{18}$$

where we have made use of the relation $\theta^2 = [(2\kappa-3)/2\kappa] \times (2k_B T_\kappa/m)$. In the Alfvén-wave frame, the energy-conservation equation is

$$v_\perp^2(t) + \big[v_{//}(t) - v_A\big]^2 = v_\perp^2(0) + \big[v_{//}(0) - v_A\big]^2 \tag{19}$$

and from Eq. (18), we can obtain the asymptotic parallel temperature

$$T_{//} = T_\kappa\left(1 + \frac{2\kappa-3}{2\kappa}\frac{v_A^2}{\theta^2}\frac{B_k^4}{B_0^4}\right) \tag{20}$$

When $\kappa \to \infty$, Eqs. (16)–(18), (20) describe the heating of Boltzmann ions by an Alfvén wave. In this situation, these results are qualitatively in agreement with Refs. [36,38].

3. Simulation model and results

We now present the test-particle calculations, using one dimension in space and three dimensions in velocity, performed to demonstrate the validity of the above analysis. The Alfvén wave propagates along the background magnetic field in the positive z direction in the laboratory frame. We will follow the evolution of test protons. The frequency of the Alfvén wave is $\omega = 0.05\Omega_p$. The Alfvén frequency is therefore much less than the proton cyclotron frequency Ω_p, so the cyclotron resonance condition cannot be satisfied. The total magnetic energy of the wave is kept constant, but we consider two values of B_k^2/B_0^2, namely, $B_k^2/B_0^2 = 0.089$ and $B_k^2/B_0^2 = 0.188$. The equations of motion are solved using the Boris algorithm, and the time step is $\Delta t = 0.025\Omega_p^{-1}$. The total number of particles is 200 000, and initially, the particles are evenly distributed in 512 grid cells, each of size $2v_A\Omega_p^{-1}$, and the velocity distribution is a Kappa distribution. Periodic boundary conditions are used. The average parallel velocity, perpendicular temperature and parallel temperature are obtained as follows: We calculate

$$U_{//} = \langle v_z\rangle, \quad T_\perp = (m_p/2k_B)\sum_{i=x,y}\big\langle\big(v_i - \langle v_i\rangle\big)^2\big\rangle \quad \text{and}$$

$$T_{//} = (m_p/k_B)\big\langle\big(v_z - \langle v_z\rangle\big)^2\big\rangle$$

in each grid cell (where the angular brackets denote averaging over a cell) [36,37]. Finally, these quantities are averaged over all grid cells. This procedure eliminates any possible contribution of the perturbed wave velocity to the temperatures, as does the analytical model.

Figs. 1 and 2 display the evolution of the normalized perpendicular temperature $T_\perp/T_\kappa$, parallel temperature $T_{//}/T_\kappa$, and average parallel velocity $U_{//}/V_A$ for cases A and B, respectively. The "shaded areas" are associated with ion gyrations, and at this stage, the randomized heating is not fully developed, and the temperatures oscillate with time. The families of κ protons and Boltzmann protons acquire identical average parallel velocities $U_{//}/V_A \approx 0.09$ at the asymptotic stage ($\Omega_p t = 920$) in Fig. 1(c) and $U_{//}/V_A \approx 0.19$ at $\Omega_p t = 1080$ in Fig. 2(c). The oscillation of the temperatures nearly disappears at this stage. The κ protons exhibit perpendicular temperatures and parallel temperatures of $(T_\perp/T_\kappa, T_{//}/T_\kappa) \approx (3.5, 1.2)$ for $\kappa = 2$, $(5.5, 1.5)$ for $\kappa = 3$, $(9, 1.7)$ for $\kappa = 10$ and $(10.0, 1.8)$ for the Boltzmann case in Fig. 1(a), (b), and they exhibit $(T_\perp/T_\kappa, T_{//}/T_\kappa) \approx (10.1, 3.0)$ for $\kappa = 3$, $(14.5, 3.8)$ for $\kappa = 5$, $(17.1, 4.2)$ for $\kappa = 10$ and $(19.8, 4.8)$ for the Boltzmann case in Figs. 2(a) and 2(b). The numerical results are qualitatively consistent and in reasonable agreement with the analytical results. The proton pickup increases as the κ parameter increases, and the heating is dominant in the perpendicular direction. Because of the thermal non-equilibrium factor, different κs that indicate different initial temperatures, the heating effect of the κ protons increases as their initial temperature decreases. The heating of the κ protons is weaker than that of the Boltzmann protons, and when $\kappa \to \infty$, the heating effects become identical. Proton heating and bulk acceleration by the Alfvén wave can also be observed in Fig. 3. In this figure, scatter plots between 200 and $500V_A\Omega_p^{-1}$ at various times, $\Omega_p t = 0$, 40, and 1000, are presented; they illustrate the heating processes of Boltzmann protons and κ protons in a self-explanatory manner. Here, the input parameters are $B_k^2/B_0^2 = 0.089$ and $\theta/v_A = 0.1$. Figs. 3(a) and 3(b) depict the velocity components in the x and parallel directions, respectively. At $\Omega_p t = 0$, the protons indicated in red and black satisfy the κ distribution ($\kappa = 2$) and the Boltzmann distribution, respectively. In comparison with Boltzmann particles, κ particles exhibit enhanced high-energy tails; namely, the initial temperature of the latter is higher. At $\Omega_p t = 40$, the protons are trapped by the electric field of the Alfvén wave and obtain average velocities in both the parallel and perpendicular directions. However, there is no obvious heating at this time. At $\Omega_p t = 1000$, the heating of the protons is obvious.

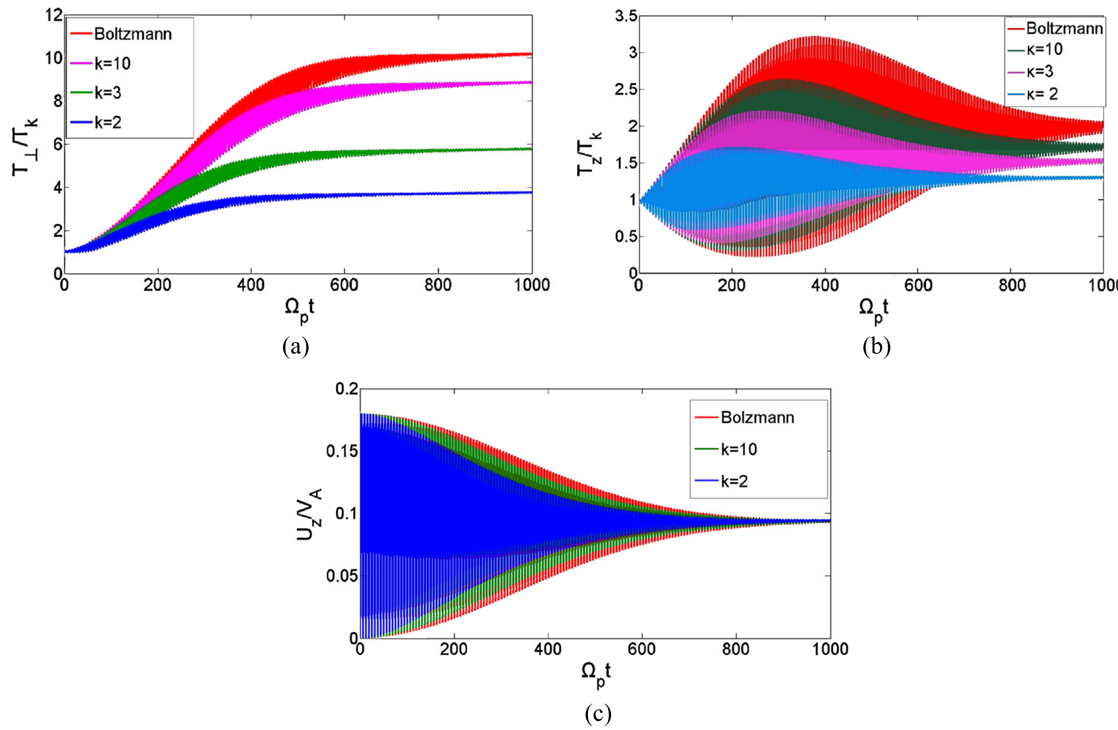

Fig. 1. The temporal evolution of the parallel (a) and perpendicular (b) kinetic temperatures and the average parallel velocity for various values of the κ parameter and $B_k^2/B_0^2 = 0.089$.

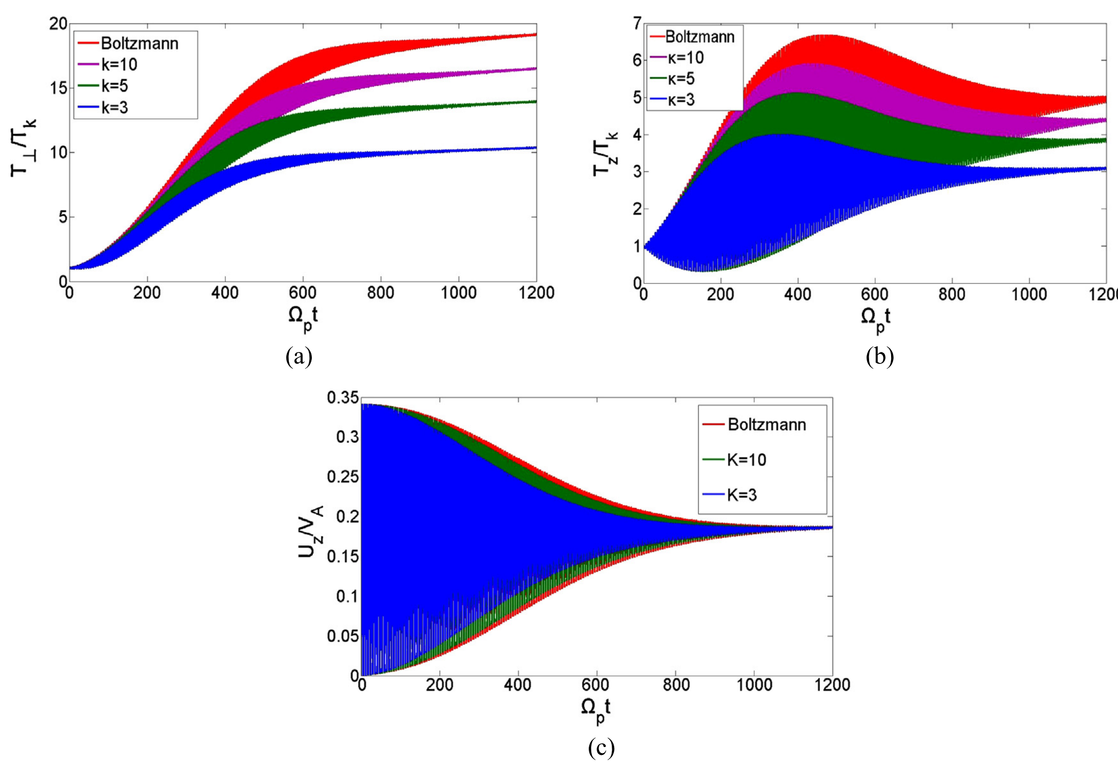

Fig. 2. The temporal evolution of the parallel (a) and perpendicular (b) kinetic temperatures and the average parallel velocity for various values of the κ parameter and $B_k^2/B_0^2 = 0.188$.

The heating is more efficient in the perpendicular direction, and the protons have an average parallel velocity of approximately $0.09v_A$. It is apparent that κ protons always have a high-energy tail during the heating process, which means that the κ protons acquire higher temperatures.

4. Summary

The physical mechanism of the heating can be described as follows: Initially, the average velocity of both κ and Boltzmann ions is zero, then ions are rapidly picked up by the Alfvén wave, primarily

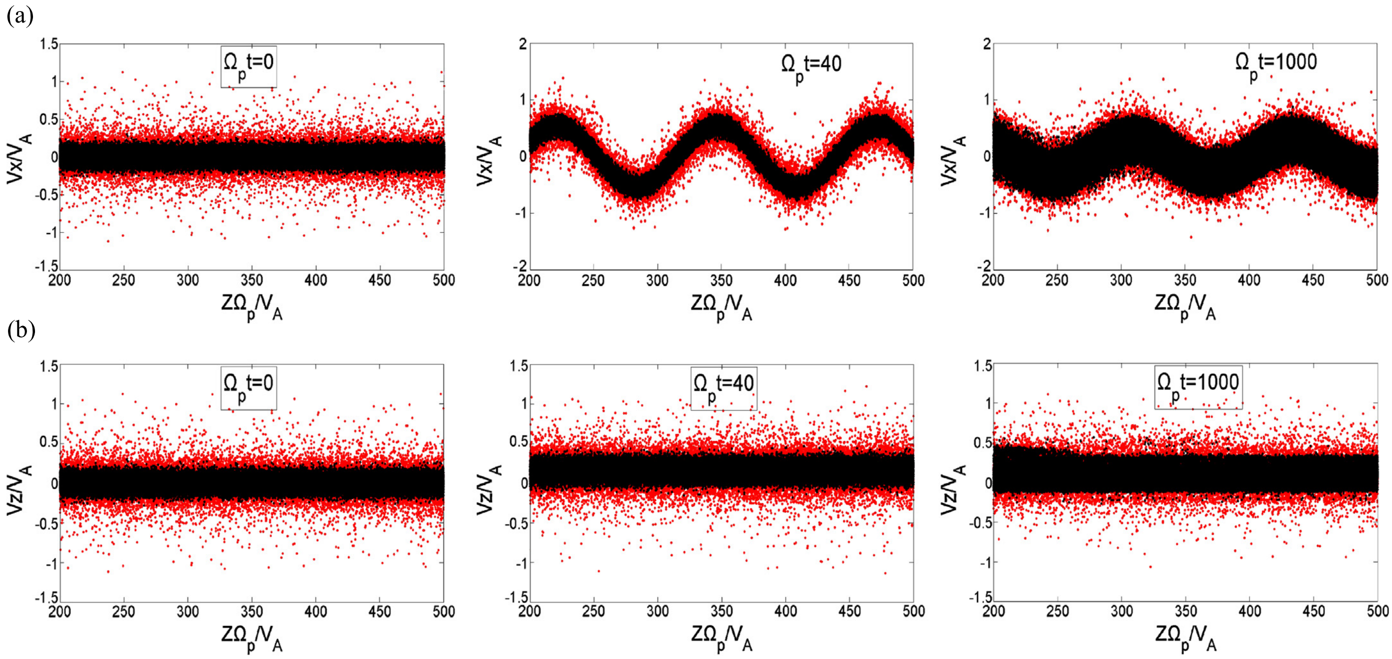

Fig. 3. Velocity scatter plots of the test particles between 200 and $500V_A\Omega_p^{-1}$ at various times, $\Omega_p t = 0$, 40, and 1000, for input parameters $(B_k^2/B_0^2, \theta/v_A) = (0.089, 0.1)$; the red dots indicate $\kappa = 2$ protons, and the black dots indicate Boltzmann protons. Panels (a) and (b) display the scatter plots of the velocity components in the x and parallel directions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

in the transverse direction. In this way, the ions acquire an average perpendicular velocity. The parallel thermal motions of the ions at a given location produce phase differences (randomization) among the ions, resulting in the heating of the ion population. Because of the initial thermal non-equilibrium suprathermal tail, the heating effect of κ ions is never more efficient than that of Boltzmann ions.

In summary, we demonstrated, both analytically and numerically, the heating of κ ions in a low-beta plasma by a low-frequency Alfvén wave of finite amplitude. In our model, the results illustrate that

(1) the heating effects of the κ ions in the perpendicular and parallel directions increase as the κ parameter increases;
(2) when $\kappa \to \infty$, the heating effects of κ and Boltzmann ions become identical;
(3) all members of the family of κ ions gain an identical average parallel velocity at the asymptotic stage; and
(4) the pickup of ions occurs predominantly in the perpendicular direction.

References

[1] P.A. Isenberg, J.V. Hollweg, J. Geophys. Res. 87 (1982) 5023.
[2] P.A. Isenberg, J.V. Hollweg, J. Geophys. Res. 88 (1983) 3923.
[3] H. Abe, H. Okada, R. Itatani, M. Ono, H. Okuda, Phys. Rev. Lett. 53 (1984) 1153.
[4] S.R. Cranmer, G.B. Field, J.L. Kohl, Astrophys. J. 518 (1999) 937.
[5] C.Y. Tu, E. Marsch, J. Geophys. Res. 106 (2001) 8233.
[6] J.A. Araneda, E. Marsch, A.F. Viñas, Phys. Rev. Lett. 100 (2008) 125003.
[7] H.S. Snyder, Phys. Rev. Lett. 27 (1971) 1349.
[8] A. Hasegawa, L. Chen, Phys. Rev. Lett. 32 (1974) 454.
[9] F.F. Chen, Introduction to Plasma Physics and Controlled Fusion, Plenum, New York, 1984.
[10] L. Chen, Z. Lin, R. White, Phys. Plasmas 8 (2001) 4713.
[11] R.B. White, L. Chen, Z.H. Lin, Phys. Plasmas 9 (2002) 1890.
[12] C.S. Wu, P.H. Yoon, J.K. Chao, Phys. Plasmas 4 (1997) 856.
[13] Y. Li, P.H. Yoon, C.S. Wu, et al., Phys. Plasmas 4 (1997) 4103.
[14] Z.H. Guo, C. Crabtree, L. Chen, Phys. Plasmas 15 (2008) 032311.
[15] C.B. Wang, C.S. Wu, P.H. Yoon, Phys. Rev. Lett. 96 (2006) 125001.
[16] C.S. Wu, P.H. Yoon, Phys. Rev. Lett. 99 (2007) 075001.
[17] J.A. Miller, Astrophys. J. 376 (1991) 342.
[18] D.A. Gates, N.N. Gorelenkov, R.B. White, Phys. Rev. Lett. 87 (2001) 205003.
[19] E.D. Fredrickson, N. Gorelenkov, et al., Phys. Plasmas 9 (2002) 2069.
[20] T.X. Zhang, B. Li, Phys. Plasmas 11 (2004) 2172.
[21] Y. Zhang, W.W. Heidbrink, et al., Phys. Plasmas 15 (2008) 012103.
[22] S.P. Christon, D.G. Mitchell, et al., J. Geophys. Res. 93 (1988) 2562.
[23] M. Maksimovic, V. Pierrard, P. Riley, Geophys. Res. Lett. 24 (1997) 1511.
[24] C.C. Chaston, Y.D. Hu, B.J. Fraser, Geophys. Res. Lett. 22 (1997) 2913.
[25] M. Øieroset, R.P. Lin, T.D. Phan, D.E. Larson, S.D. Bale, Phys. Rev. Lett. 89 (2002) 195001.
[26] M. Maksimovic, V. Pierrard, J.F. Lemaire, Astron. Astrophys. 324 (1997) 725.
[27] Hai-Feng Liu, Shi-Qing Wang, Ke-Hua Li, Phys. Plasmas 20 (2013) 104504.
[28] O.A. Pokhotelov, R.A. Treumann, et al., J. Geophys. Res. 107 (2002) 1312.
[29] R.A. Treumann, C.H. Jaroschek, M. Scholer, Phys. Plasmas 11 (2004) 1317.
[30] R.A. Treumann, Phys. Scr. 59 (1999) 204.
[31] M.P. Leubner, Planet. Space Sci. 48 (2000) 133.
[32] M.P. Leubner, Astrophys. J. 604 (2004) 469.
[33] M.P. Leubner, Phys. Plasmas 11 (2004) 1308.
[34] R.A. Treumann, C.H. Jaroschek, Phys. Rev. Lett. 100 (2008) 155005.
[35] L.-N. Hau, W.-Z. Fu, Phys. Plasmas 14 (2007) 110702.
[36] Q.M. Lu, X. Li, Phys. Plasmas 14 (2007) 042303.
[37] Q.M. Lu, L. Chen, Astrophys. J. 704 (2009) 743.
[38] K.H. Li, X.Y. Gong, et al., Phys. Plasmas 19 (2012) 072118.